

Dynamics of a stored Zeeman coherence grating in an external magnetic field

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Abstract. We investigate the evolution of a Zeeman coherence grating induced in a cold atomic cesium sample in the presence of an external magnetic field. The gratings are created in a three-beam light storage configuration using two quasi-collinear writing laser pulses and reading with a counterpropagating pulse after a variable time delay. The phase conjugated pulse arising from the atomic sample is monitored. Collapses and revivals of the retrieved pulse are observed for different polarizations of the laser beams and for different directions of the applied magnetic field. While magnetic field inhomogeneities are responsible for the decay of the coherent atomic response, a five-fold increase in the coherence decay time, with respect to no applied magnetic field, is obtained for an appropriate choice of the direction of the applied magnetic field. A simplified theoretical model illustrates the role of the magnetic field mean and its inhomogeneity on the collective atomic response.

1. Introduction

The mapping of optical information into an atomic ensemble, a phenomenon usually named light storage (LS), plays a fundamental role for both classical and quantum information processing [1]. To date several observations of LS have been reported both in thermal and in cold atomic systems [2, 3, 4, 5, 6, 7]. Long storage times as well as the possibility of controlling and manipulating the stored information [8, 9], is of essential importance for the realization of any practical quantum protocol. In most of the experimental observations of LS, ground state hyperfine levels of alkali atoms are employed to store the optical information into Zeeman coherences. These coherences may be conveniently manipulated by external magnetic fields [10, 11, 12]. However, they are also very sensitive to stray magnetic fields gradients, which can strongly reduce the coherence time of the system [13, 14]. Collapses and revivals due to Larmor precession of Zeeman coherence associated with different hyperfine ground states of rubidium atoms have already been observed, both using Poissonian classical light and single photon quantum states [15, 16]. Recently, we have demonstrated the coherent Larmor precession of orbital angular momentum of light stored into Zeeman coherences of cesium atoms [17]. It is also worth mentioning the recently demonstrated long-lived gradient echo memory, which is a different technique for LS and allows the control of the retrieved pulse sequence [18, 19].

In this work we investigate the coherent evolution of a light grating stored onto the ground state Zeeman coherence in the presence of an external dc magnetic field. The presence of the magnetic field give rise to a periodic evolution of the atomic state (Larmor precession) that determines an oscillatory response of the retrieved pulse efficiency as a function of the time separation between the writing and reading of the coherence grating. Nevertheless, the coherent response of the sample is damped as a consequence of the dephasing of the individual atomic contributions due to residual magnetic field inhomogeneities. Interestingly enough, the damping time of the total atomic response strongly depends on the direction of the applied magnetic field. We have observed a five-fold increase in the coherence decay time, with respect to the damping time at zero applied field, for a particular direction of the applied magnetic field.

Precise theoretical modelling of our observations is prevented by the lack of a priori knowledge of the residual magnetic field in the sample. Nevertheless, the essential features of the experimental results are qualitatively reproduced by a simplified theoretical model, based on optical Bloch equations, describing the atomic state evolution in the presence of a homogeneous magnetic field together with an ad hoc inhomogeneous field. This model accounts for the oscillations (revivals) of the retrieved pulse amplitude as well as for the variation of the storage decay time with magnetic field direction. The key role played by the relative orientations of the mean magnetic field and its inhomogeneity is also illustrated through the classical calculation of the precession of an ensemble of magnetic dipoles in the presence of an inhomogeneous field.

2. Experimental setup and results

The experimental apparatus is similar to the one previously described in [7] and employs cold cesium atoms obtained from a magneto-optical trap (MOT). The atoms are initially prepared into the $6S_{1/2}(F = 3)$ hyperfine ground state by optical pumping induced by the MOT trapping beams, with the repumping beam switched off for about 1 ms. The MOT quadrupole magnetic field is switched off during the optical pumping process and the subsequent light storage sequence. Three pairs of orthogonal Helmholtz coils are used to compensate for stray magnetic fields. To write and read the coherence grating we use light from an external cavity diode laser, locked to the cesium D2 transition $6S_{1/2}(F = 3) \leftrightarrow 6P_{3/2}(F' = 2)$. Immediately after the optical pumping interval, two laser beams are incident on the atomic cloud making a small angle of $\theta = 60$ mrad as indicated in Fig. 1-(a). These two beams, named from now on as the grating writing beams, W and W' , have opposite circular polarizations and induce a Zeeman coherence grating between pairs of Zeeman sublevels, as indicated in the Fig.1 (a). The writing beams have their intensity controlled by a pair of acousto-optic modulators (AOM) and are applied during a time long enough ($\approx 40 \mu\text{s}$) so to allow the system to reach a steady state regime. During the coherence-grating writing interval, an external dc magnetic field is applied, either along the propagation direction of the W beam (chosen as quantization axis in Fig. 1) or orthogonal to this axis, by two additional independent pairs of Helmholtz coils shown in Fig.1. After the switching off of the writing beams, the induced Zeeman coherence grating evolves in the presence of the external magnetic field undergoing Larmor precession. The instantaneous Zeeman coherence grating can be used to retrieve the optical field (the diffracted beam D) by switching on a reading beam, R , counterpropagating to the writing beam W and having a circular polarization opposite to that of this beam, as shown in Fig. 1-(b). For this beam geometry, the retrieved light pulse is phase conjugated to the writing beam W' and counterpropagating with respect to this beam. The reading beam also passes through an independent pair of AOMs that allows for the variation of the time interval between writing and reading processes as indicated in the time sequence shown in Fig. 1-(c). We have experimentally verified that the retrieved beam has a polarization which is orthogonal to the polarization of the reading beam as indicated in Fig. 1-(b).

The retrieved signal intensity for different storage times is shown in Fig.2-(a) corresponding to the polarization configuration specified in Fig. 1-(a),(b) for the case where no external dc magnetic field is applied. For these data, the intensities of the writing beams W and W' are equal to 17.6 mW/cm^2 and 1.1 mW/cm^2 respectively, while the intensity of the reading beam is equal to 7.2 mW/cm^2 . As can be observed, the retrieved signal peak intensity has an approximately exponential decrease with a free decay time of the order of $4 \mu\text{s}$ [7]. This measured coherence decay time is mainly determined by the non compensated residual magnetic field gradients [14]. The MOT temperature was estimated to be in the range of mK and the measured density of atoms in the $F=3$ ground state was of the order of $n \approx 10^{10} \text{ cm}^{-3}$. From these values, we

estimated the collision rate to be of order of $\Gamma_{coll} \approx 0.2$ KHz [20], therefore having a negligible effect in the decoherence process. Also, at the estimated temperature, the time needed for an atom to move one grating period is much larger than the measured coherence time, therefore ruling out the effect of atomic motion.

The dynamics of the retrieved signal changes completely when a dc magnetic field of magnitude $B_x=0.7$ G is applied perpendicularly to the propagation axis, i.e., along the x direction. The observed result is presented in Fig. 2-(b), which clearly shows a periodic oscillation of the retrieval efficiency with a period of approximately $T_L=4.4 \mu s$. On the other hand, as shown in Fig. 2-(c), if the dc magnetic field is applied along the z axis, we also observe a periodic modulation of the retrieved signal, but now with smaller visibility and a period given approximately by $T_L/2=2.2 \mu s$. These values are consistent with Larmor frequency predicted for the hyperfine level ($F = 3$), which is given by $\Omega_L = g_F \mu_B B$, with $g_F = -1/4$ the Landé factor, μ_B the Bohr magneton and B the magnitude of the magnetic field [21]. From the applied magnetic field in our setup we estimate a Larmor period of $T_L = 2\pi/\Omega_L=4.1 \mu s$, which agrees reasonably well with the observed value.

A simple picture can be given for a qualitative understanding of the observed behavior by considering the evolution of the coherent superposition of Zeeman sublevels, prepared by the writing beams, in the presence of the applied magnetic field. Considering the larger intensity of beam W with respect to W' , one should expect orientation of the atomic system with the largest population in the Zeeman sublevel with the highest M_F value. Thus, in the former case where the magnetic field is perpendicular to the quantization direction, the magnetic hamiltonian will couple the Zeeman states differing by $\Delta M_F = \pm 1$ and the probability amplitude associated to each component of the initial superposition state will oscillate at the Larmor frequency, therefore repeating itself after the Larmor period. It is worth noticing that after half the Larmor period the evolution changes the probability amplitude associated with a sublevel M_F into that of $-M_F$ and vice-versa, therefore also repeating the value of the Zeeman coherence. However, at this instant the reading beam will be coupled to a different transition, which can lead to a decrease of the diffracted signal. Indeed, in the limit of strong saturation of the reading beam, the signal is reduced by the ratio between the two Clebsch-Gordan coefficients of the transitions coupled by the reading in the two different situation [7]. Differently, when the dc magnetic field is applied along the quantization direction, each component of the initial superposition will simply acquire a phase factor proportional to $\exp(iM_F \hbar \Omega_L)$ and the Zeeman coherences associated with sublevels differing by $\Delta M_F = 2$ will therefore oscillate with a period $T_L/2$. This simple consideration accounts qualitatively well for the series of collapses and revivals observed experimentally.

In addition, we have performed similar measurements for the case where the writing beams have orthogonal linear polarization with the reading beam being linearly polarized parallel to the polarization of the writing beam W' . In this case, alignment is produced

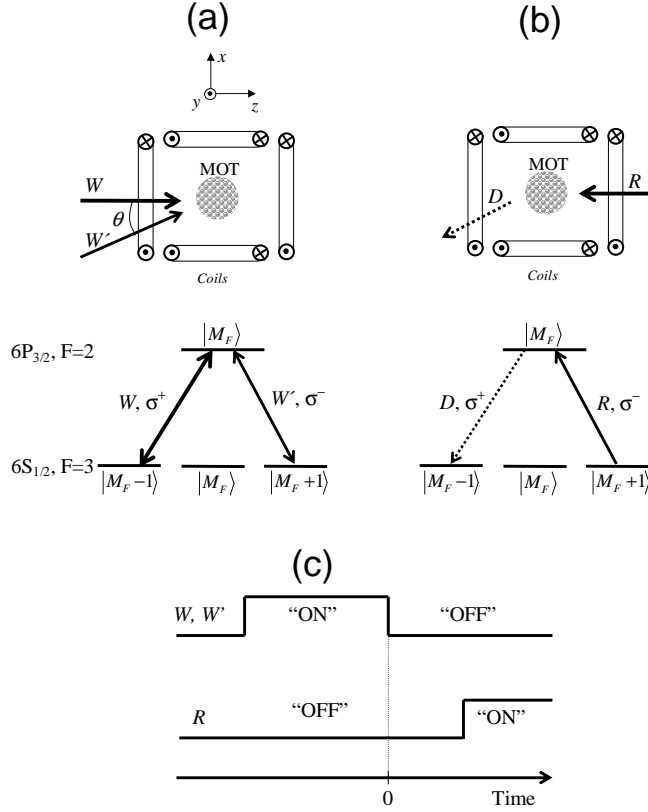


Figure 1. (a) Incident writing beams (W and W') configuration and partial Zeeman level scheme of the hyperfine transition $(F = 3) \leftrightarrow (F' = 2)$, showing the coupling of the writing beams. (b) Spatial configuration and coupling of the incident reading (R) and the retrieved diffracted (D) beams. The beams W and W' make a small angle θ and are circularly polarized with opposite handedness, while the beam R is counterpropagating to the beam W and have a circular polarization opposite to this beam. The diffracted beam is detected in a direction opposite to the beam W' . (c) Switching time sequence for the writing and reading fields.

in the atomic system leading to a symmetric distribution of the Zeeman population. In such case, for an applied transverse magnetic field, after half the Larmor period all the Zeeman coherences and populations repeat themselves and therefore the retrieved signal oscillates with half the Larmor period. This behavior was experimentally observed. Finally, we also have measured the evolution of the Zeeman coherence grating for different values of the external magnetic field. In Fig. 3 we plot the inverse of the Larmor period as a function of the transverse magnetic field amplitude. As expected, a linear dependence is observed.

The most remarkable feature of the measurements presented in Fig. 2 is the observed increase of the coherence decay time when the dc magnetic field is applied. As mentioned before, the measured coherence decay time is mainly determined by

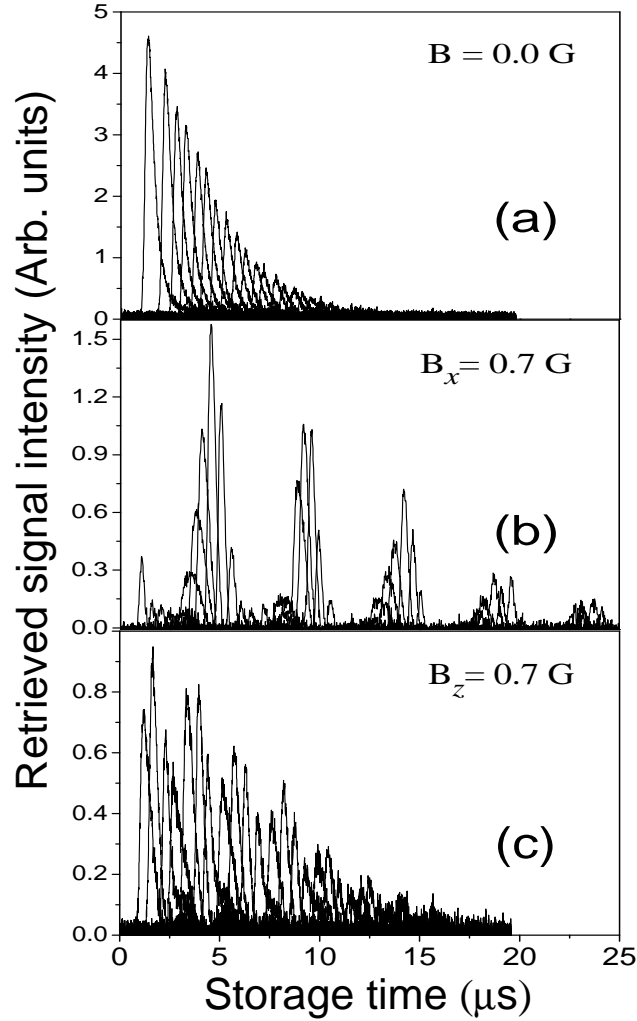


Figure 2. Retrieved signal for different storage times when: (a) no external dc magnetic field is applied; (b) a $B_x=0.7 \text{ G}$ dc magnetic field is applied along the x direction; (c) a $B_z=0.7 \text{ G}$ dc magnetic field is applied along the z direction. Each graphic represents a superposition of the retrieved pulses associated with different reading time.

stray magnetic field gradients that are not precisely known in our apparatus. The experimental data shown in Fig.2(b) and Fig.2(c) clearly indicate that a larger increase in the coherence time is obtained when a dc magnetic field is applied along a specific direction (x axis), which is orthogonal to the propagation direction of W and R beams, although a smaller increase is also observed when the magnetic field is applied along the propagation direction of these beams (z axis).

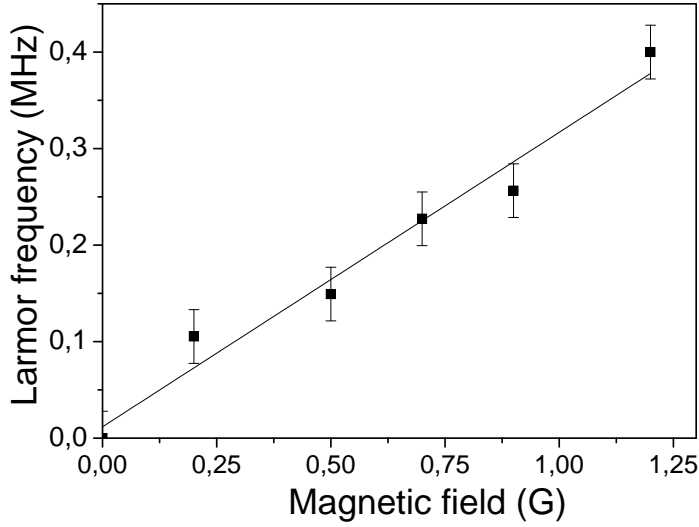


Figure 3. Measured Larmor frequency as a function of the applied transverse magnetic field. The solid line is a linear fitting.

3. Theoretical modelling

In this section we provide a simplified model of the atomic evolution in the presence of the writing and reading light pulses, which gives rise to the emission of the retrieved pulse. Although the model does not intend to precisely fit the experimental observations, the main features of the observed signals are qualitatively reproduced. The model gives a clear indication of the relevant physical parameters determining the atomic evolution.

The model is based on the numerical solution of the Bloch equations for an ensemble of atoms evolving in a dc magnetic field. The calculation is a direct extension of the one presented in [22]. The reader is referred to this publication for details. We briefly remind here the main lines of the calculation. Two atomic hyperfine levels g and e are considered with well defined total angular momentum F_g and F_e respectively, connected by an optical transition. All Zeeman sublevels are taken into account. The excited state e has a total decay rate Γ that determines the relaxation of the excited state population and of the optical coherence. Unlike in [22], however, we do not include in the model any relaxation mechanism for the ground state coherence. The light field acting upon the atoms is resonant with the atomic transition. The Bloch equations are numerically integrated for successive time intervals, corresponding to the light storage sequence with square pulses. Each interval corresponds to the duration of an applied light pulse. During each interval, the optical field has a well defined amplitude, polarization and phase. In a given time interval, the optical field may correspond to a unique (R) light pulse or be the total field resulting from two light beams ($W + W'$).

Our simplified model does not include light propagation effects across the atomic sample. The atoms are subject to a single optical field, which can however have one

or two polarization components. In consequence, no spatial grating is represented in the model. Numerically integrating the Bloch equations, we calculate the atomic polarization during the reading time-interval. We consider the beams W and W' with orthogonal linear polarizations. Beams W' and R have the same polarization. Notice that the choice of linear polarizations is different from the experimental situation previously described. The reasons for such choice are explained next.

We are interested in the transient atomic response corresponding to the emission of the “phase conjugate” retrieved pulse. In the experiment such pulse is characterized by its propagation direction opposite to that of field W' . Since our calculation does not include propagation, phase matching effects determining the emission of light in well defined directions are not accounted for and cannot be used to characterize the “phase conjugate” retrieval. In consequence, only polarization can be used in the calculation for the identification of the “phase conjugate” retrieved pulse. The corresponding light intensity is proportional to the square modulus of the optical coherence of the atomic sample with polarization opposite to that of fields R and W' .

The fact that in the numerical simulation, only the light polarization can be used to separate the “phase conjugate” retrieved light pulse, imposes some constraints in the choice of the light polarizations. In particular, we have to be careful to choose the common polarizations of fields R and W' such that it will not acquire a component along the “detected” polarization (the same as W) as a consequence of Faraday rotation under the dc magnetic field. Such effect, that would contaminate the retrieved pulse with a background independent of the previously stored light pulses, is not relevant in the experiment where only the phase conjugate response is phase matched in the direction opposite to that of field W' .

We have considered in the numerical simulation a linear polarization along axis x for field W , and linear polarization along y for fields W' and R . The “phase conjugate” retrieved pulse is due to the atomic polarization during the reading interval oriented along x . Two orientations of the mean magnetic field were considered: x and y .

In cold atoms, where atomic motion and collisions can be neglected, the decay of the coherent response of the atomic sample comes from dephasing of the contributions of atoms in different parts of the sample. Such dephasing is due to the presence of an inhomogeneous magnetic field along the sample that causes different evolutions of the atomic ground state [13, 14]. In order to simulate the inhomogeneous response of the atomic sample, we have calculated the evolution of homogeneous atomic sub-samples subject to randomly distributed magnetic fields. The total response is given by the sum of the optical coherence in each sub-sample. We have considered in our calculation different orientations of the mean value \mathbf{B} of the vector magnetic field. However, in order to simplify the calculation and illustrate the importance of the inhomogeneity orientation, we have only considered magnetic field departures from the mean value with a constant orientation (along x). A Gaussian distribution of the magnetic field variation was assumed with variance ΔB .

Figures 4-6 show the result of the numerical simulations of the retrieved “phase

conjugate" light pulse as a function time. Although the simulation reproduces the complete light storage sequence, only the storage and retrieval intervals are represented. The origin of the time axis corresponds to the simultaneous turn off of the two writing fields W and W' . In each figure, several retrieved pulses are presented corresponding to different durations of the dark (storage) interval. For simplicity, the calculations were carried on a model transition $F_g = 1 \rightarrow F_e = 0$. Other choices of the angular momenta give qualitatively similar results. The amplitudes of the applied fields are determined by the corresponding reduced Rabi frequency for the transitions. The simulations presented in Figs. 4-6 correspond to reduced Rabi frequencies of 0.5Γ , 0.25Γ and 0.125Γ for fields W , W' and R , respectively. The duration of the writing period (W and W' both present) was taken as $10.6\mu s$

Figure 4 show the retrieved pulses obtained for zero mean magnetic field in the presence of a Gaussian distributed inhomogeneous magnetic field oriented along x with variance $g_F\mu_B\Delta B = 5 \times 10^{-3}\Gamma$. The magnetic field inhomogeneity is responsible for the observed decay of the retrieved pulse amplitude with a characteristic decay time of the order of a few microseconds.

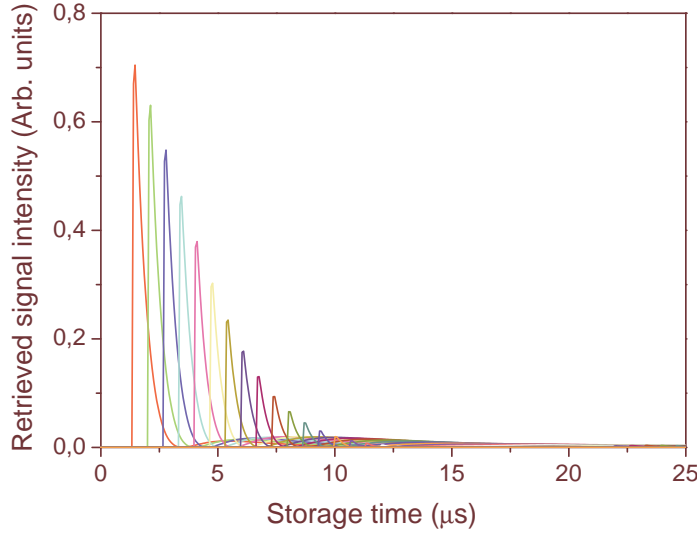


Figure 4. (Color online) Calculated retrieved light pulses for different storage times for an ensemble of atoms in an inhomogeneous magnetic field oriented along axis x with zero mean. The time origin corresponds to the simultaneous turn off of the writing fields. Each trace initiates at a time corresponding to the turn on of the reading field.

When, in addition to the inhomogeneous magnetic field distribution, a dc magnetic field with $g_F\mu_B B = 2 \times 10^{-2}\Gamma$ is applied along axis x an oscillation is present at twice the corresponding Larmor frequency (Fig. 5). The envelope decay time of the retrieved pulses amplitude oscillation is similar to that in Fig. 4. Notice that the shape of the individual pulses varies depending on whether the retrieval process occurs during the rising or the falling of the magnetically induced oscillation. Broad pulses are observed

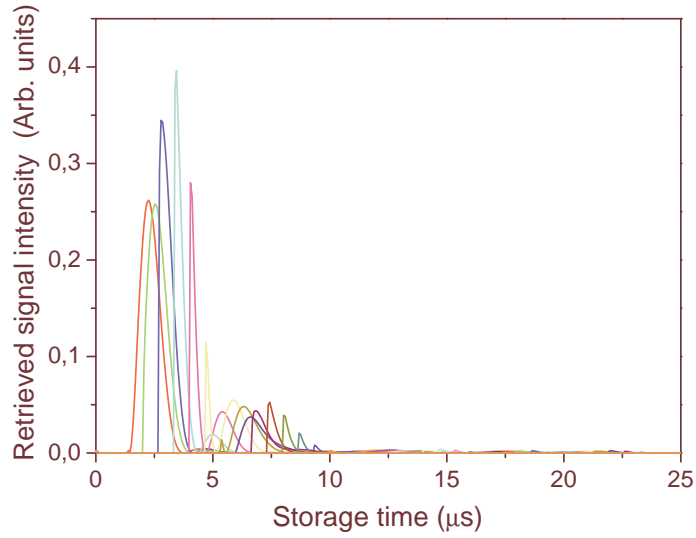


Figure 5. (Color online) Same as Fig. 4 for an ensemble of atoms in the presence of a mean magnetic fields oriented along x in addition to a random distribution of magnetic fields oriented along axis x with zero mean.

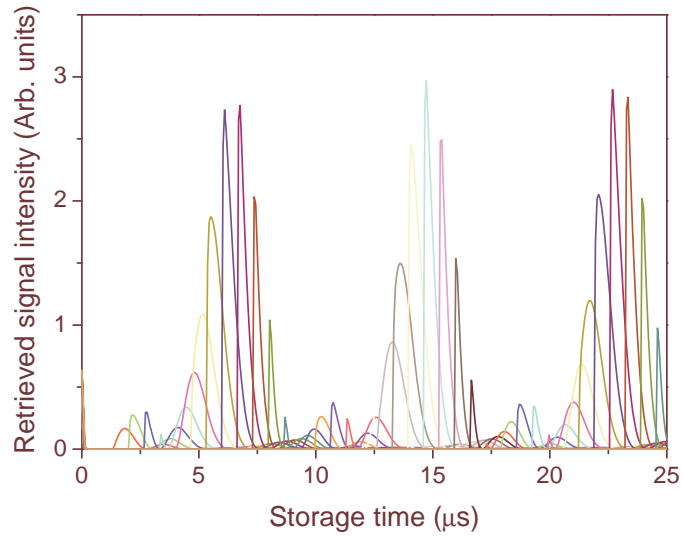


Figure 6. (Color online) Same as Fig. 4 for an ensemble of atoms in the presence of a mean magnetic fields oriented along y in addition to a random distribution of magnetic fields oriented along axis x with zero mean.

on the rising side of the oscillation and narrow ones on the falling side. A similar effect is observed in the experiment (See Fig. 2). In the presence of the magnetic field, individual retrieved pulses also present oscillations that are rapidly damped with a decay time dependent on the R pulse intensity.

A dramatically different behavior is seen in Fig. 6 where the mean magnetic field is oriented along axis y while the field inhomogeneity is given by field variations along x . In this case, the oscillation of the peak of the retrieved pulse is clearly visible while the envelope decay is almost unnoticeable on the time scale of the figure. Notice the presence of two frequency components in the oscillation: a larger amplitude oscillation at the Larmor frequency and a smaller oscillation at twice that frequency.

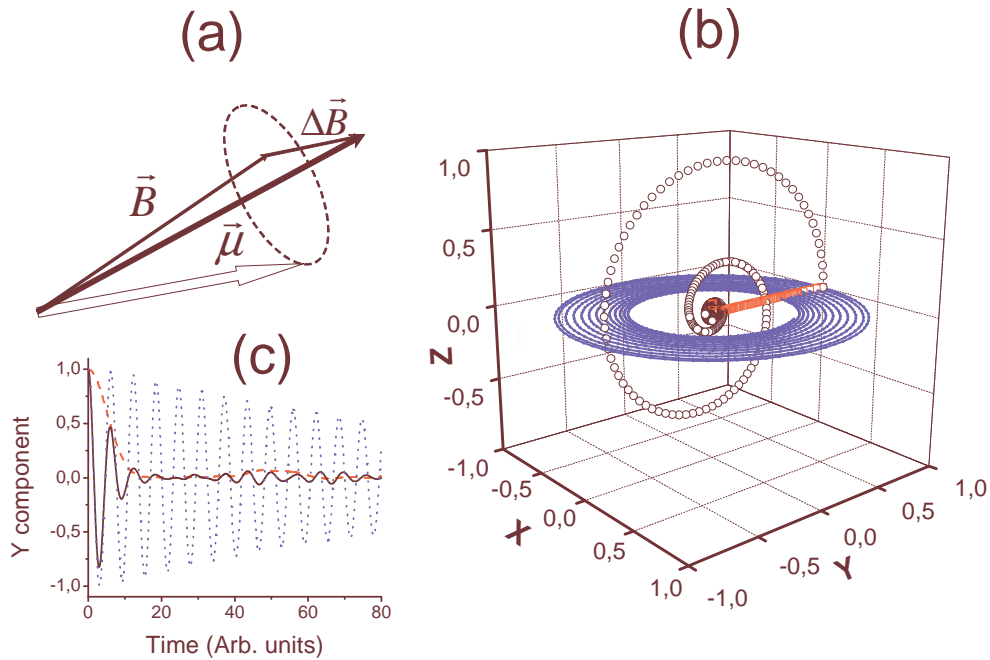


Figure 7. Color online. a) Precession of a magnetic dipole $\vec{\mu}$ around a magnetic field. b) Trajectory of the total magnetic moment for an ensemble of magnetic dipoles for different orientations of the mean magnetic field: no mean field (hollow red squares); mean field along x (hollow black circles), mean field along z (solid blue line). The magnetic field variations with respect to the mean value are oriented along x . c) y axis projections of the total magnetic moment: no mean field (dashed red); mean field along x (solid black), mean field along y (dotted blue).

Figure 6 dramatically illustrates the importance of the relative orientation of the mean magnetic field and the field inhomogeneity for the effective decay rate of the retrieved pulse amplitude. When the mean field orientation is perpendicular to the inhomogeneous field, the dephasing of the contributions to the signal from atoms at different locations occurs at a much slower rate. This effect has a purely classical origin

as can be illustrated by considering the (classical) motion of an ensemble of magnetic dipoles precessing in a homogeneous magnetic field. We present in Fig. 7 the evolution of the total magnetic dipole, initially oriented along y evolving in a magnetic field with inhomogeneity in the x component. If the mean magnetic field is zero or oriented along x a relatively short decay of the total dipole is observed. For a mean magnetic field oriented along z the evolution of the total dipole corresponds to a slowly damped precession. This difference in dephasing time can be simply understood by noting that while an inhomogeneous field oriented along the mean field will produce a first order correction to the total field, a magnetic field variation in a direction perpendicular to the mean field only causes a second order total field modification. The same argument can be used for the atomic evolution considered previously.

4. Discussion and Summary

In spite of the simplicity of the theoretical model presented above and the use of a different choice of optical polarizations, several features of the experimental observations are qualitatively reproduced. An almost exponential decay of the retrieved pulse amplitude is observed in the absence of a mean magnetic field illustrating the inhomogeneous nature of the coherence decay. In this case all retrieved pulses have the same shape with a characteristic decay time dependent on the reading pulse intensity. When a dc magnetic field is present, the retrieved pulse amplitude oscillates at the Larmor frequency and/or its second harmonic. This is consistent with the expected evolution of the sample orientation or alignment, respectively. In the general case, both frequencies are present in the evolution of the atomic coherence. The individual retrieved pulses have different shapes depending on the turn-on time of the reading pulse with respect to the magnetic oscillation cycle. Most importantly, the similarities between experimental results and the calculated evolution illustrates the decisive role of the magnetic field inhomogeneity on the coherence signal decay. When the dc field is applied perpendicular to orientation of the local variations of the magnetic field a significant enhancement in the coherence decay can be observed. Such feature may be used for the characterization of unknown field inhomogeneities.

The above result can be seen as a simple means of coherence control in a sample where the decoherence is a consequence of spatial inhomogeneity of the atomic sample. Coherence control has attracted considerable attention in recent times due to its crucial role in the preservation of quantum information. In the case where decoherence results from the coupling of the observed system to a large environment, and is thus homogeneous and irreversible in nature, coherence control poses a really challenging problem. Significant progress has been recently achieved in this field both with passive and active control protocols relying on the shaping of the interaction of the small system with its environment [23]. In the present case, however, the decoherence time for the state of individual atoms is long and the shorter observed decay of the coherent emission is the result of the dephasing of the individual atomic contributions

evolving in slightly different magnetic environments. We have shown here that the resulting effective dephasing time can be manipulated by the addition of a constant magnetic field properly oriented. However, one has to keep in mind that inhomogeneous dephasing is not intrinsically irreversible. The initial information stored in the sample is, in principle, available in the atomic sample where individual atoms undergo unitary evolution. The stored information can be recovered, by inducing the rephasing of the atomic contributions through photon echoes [24]. Moreover, the inhomogeneous nature of the atomic dephasing allows the simultaneous recording in the sample of different light pulse Fourier components. As first suggested by Mossberg [25], this allows the storage and recording of light pulses with complex temporal profiles. While early experiments used the pre-existing sample inhomogeneity, an interesting recent improvement consists in the at-will manipulation of the sample inhomogeneity by the application of a user controlled external magnetic field gradient. In such case, storage as well as manipulation (delay and reversal) of complex pulse temporal information is possible [18, 19]. Finally, it is worth emphasizing the significant progress recently achieved in the direction of suppressing the inhomogeneous dephasing altogether by eliminating the influence of the magnetic field through the use of magnetically insensitive two-photon transitions (clock transitions), where storage time of the order of millisecond have been observed [8, 9].

In summary, we have experimentally observed the Larmor precession of a coherence grating stored into the Zeeman sublevels of the cesium $6S_{1/2}(F = 3)$ ground state in the presence of an applied magnetic field. Collapses and revivals of the retrieved signal with distinct Larmor oscillation frequency were observed for different distributions of Zeeman populations and coherences associated with different polarization configuration of the writing beams. An appreciable increase in the coherence decay time was observed for a specific direction of the applied magnetic field. We have also presented a simple theoretical model based on the numerical solution of the Bloch equation including the Zeeman degeneracy which qualitatively agrees with the main experimental observations. Moreover, we have shown that the increasing in the coherence time has a even simpler and purely classical explanation. Finally, we think that the possibility of controlling the coherence time in a larger ensemble of atoms can be of considerable interest for several applications and specially for quantum information.

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